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TENSILE PROPERTIES OF ERW PIPE WELDS WITH ARTIFICIAL FLAWS

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ABSTRACT

The effect of bond-line defects on the tensile strength of electric resistance welded (ERW) pipe welds has been investigated. Circular defects up to 10 mm dia in pipe of 14 mm wall thickness do not change the mode of fracture in simple tension. The stress of failure can be described by a collapse model in which the strength is proportional to the net load-bearing area. For the pipe investigated, a Charpy V-Notch (CVN) absorbed energy of 32 J at the test temperature, the fracture stress is not toughness dependent.

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PROPRIÉTÉS EN TRACTION DE TUYAUX SOUDÉS PAR RÉSISTANCE ÉLECTRIQUE AVEC DÉFAUTS ARTIFICIELS

par

W.R. Tyson et K.C. Wang

RÉSUMÉ

On a étudié les effets de défauts à la jonction de tuyaux soudés par résistance électrique sur la résistance à la traction. Les défauts circulaires jusqu'à 10 mm de diamètre dans des parois de tuyaux de 14 mm d'épaisseur ne changent pas le mode de rupture en traction. La contrainte de rupture peut être décrite par un modèle de défaillance dans lequel la résistance est proportionnelle à la section efficace supportant la charge. Pour les tuyaux étudiés, la contrainte de rupture ne dépend pas de la ténacité, l'énergie absorbée lors d'essais Charpy à entaille en V étant de 32 joules à la température d'essai.

INTRODUCTION

ERW pipe is being considered increasingly for demanding applications, because it can be produced economically. However, because of the way it is made - essentially by hot forging - there is a risk that poor bond line properties and defects could occur if control of the process is inadequate.

The objective of the work described in this report was to investigate the effect of bond-line defects on the tensile strength of ERW pipe welds. The work forms part of a larger project to evaluate the significance of weld defects in ERW pipe on the failure pressure of the pipe, the resistance of the pipe to corrosion in the presence of H_2S, and on non-destructive ultrasonic methods of detecting defects.

MATERIALS

Materials were produced in a trial run of 324 mm (12.75 in) diameter, 14.27 mm (0.562 in) wall thickness Grade 414 (X60) ERW pipe. Flaws were artificially introduced along the bond line by means of arc strikes made on the surfaces before joining, and their locations were identified with punch marks on the coil plate. Chemical composition, mill tensile data and Charpy V notch properties provided by the supplier are shown in Tables 1 to 3.

EXPERIMENTAL PROCEDURES

Tensile specimens were cut from flattened pipe, with their long axes transverse to the pipe axis. Pipe body specimens were made to the customary strip design with a reduced section according to ASTM Standard E8. To test the weld region, notches must be placed at the weld line to force failure to occur there, because the weld is expected to have a higher tensile strength than the parent pipe. The specimen design recommended by Williams in work done at Battelle Columbus Laboratories (1), is shown in Fig. 1, and was used in this work. Pipe body specimens with notches were also prepared to compare the properties of the pipe body and the weld with the same specimen geometry.

Tensile testing at MTL was performed on a universal hydraulic testing machine under load control, and at Fleet Industries (formerly Arctec), Kanata, on a machine under displacement control [set at 2.5 mm (0.1 in.) per min]. After specimens were broken, the broken halves were fitted together and the elongation measured over a 50 mm (2 in.) gauge length. The flawed area in samples with artificial defects was measured by Quantimet optical metallography.

Metallographic sections were prepared of the as-received (undeformed) pipe containing the ERW weld, and Vickers microhardness measurements were made with a load of 500 g. Several sections were taken through fracture surfaces to determine the path of the crack.

RESULTS

A cross-section of the as-received material in Fig. 2 shows that the normalization heat treatment has extended only to about mid-thickness of the weld, leaving the inner surface in the as-welded condition. Typical hardness traverses are shown in Fig. 3 and 4. The hardness results confirm that the weld hardness is highest near the inner surface. The normalized regions of the weld (near the outer surface in Fig. 4) have hardnesses similar to or somewhat lower than those of the pipe body. There is evidence of some softening of the pipe material about 2 mm from the weld line in the as-welded condition (see Fig. 3).

Results of the tensile tests are given in Table 4. The properties of the parent pipe are well within specification for Grade 414 (X60) of 517 MPa UTS and 24% elongation required by CAN 3-Z245.1-M86, as are the mill tensile data (Table 2). The average tensile strength of pipe body samples containing a notch is higher than the properties of samples without a notch by 13%. The result is consistent with the effects of constraint on tensile properties demonstrated by Wang et al.(2).

Results from specimens notched in the weld are more variable. The elongation of welds without flaws ranged from 2.6% to 10.0%, the appearance of the fracture surface of specimens with lower elongations being flat and brittle. Macrographs of the fracture surface are shown in Fig. 5. SEM examination of specimen 13 confirmed that cleavage was the micromode of fracture in the brittle samples, the cleavage facets being larger at the inside surface of the pipe than at the outside. This behaviour is consistent with the outer surface having been normalized.

Similar variability of the fracture mode was found in the welds containing flaws, as shown in Table 4 and Fig. 6. Brittle or ductile behaviour did not correlate with flaw area but was inconsistent as with behaviour in the absence of a flaw.

There was no obvious difference, apart from the fracture surface appearance and tensile elongation, between brittle and ductile samples. Samples 1, 9 and 20 (ductile) and 15 (brittle) were sectioned through the fracture surface to see if any consistant pattern could be detected. For example, brittle fracture (sample 15) follows the bond line but in ductile samples fracture was near the bond line through about two-thirds of the thickness from the outside surface, including the normalized region, but near the inside surface follows the heat-affected zone (see Fig. 7). This behaviour is consistent with the hardness and tensile results. As shown in Figs.3 and 4, the bond line is harder than the pipe body as welded and softer after normalization, and there is a soft region at the boundary of the HAZ in the as-welded condition. The (notched) tensile strength of the weld

line is about 6% higher than that of the (notched) pipe body (Table 4). However, a difference, which possibly is significant, was found in the hardness traverse taken along or near the fusion line. As shown in Fig. 8, the hardness of the brittle fracture was the lowest of the four samples. (Note, however, that these hardnesses were measured after testing which introduces work hardening, and so are not directly comparable to those of Fig. 3 and 4.). This implies that low as-welded hardness on the fusion line signifies a weld susceptible to brittle weld-line failure, although more tests would be required to confirm this observation.

Finally, the results of the tensile tests are summarized in Fig. 9. The line shown in the figure is given by

$$\text{Tensile strength} = [690\ \text{MPa}][100 - (\text{flawed area, \%})]$$

which simply states that the tensile strength is directly proportional to the (unflawed) area of the sample. Whether the mode of failure is brittle or ductile has no significant effect on the relationship. The same is true of the welds with no flaws (Table 4); only in one case of exceptionally low elongation (Sample 13) is the tensile strength notably below the average.

DISCUSSION

The tensile strength of the ERW welds containing artificial flaws investigated in this work can be well described by a collapse model in which the strength is proportional to the ligament, i.e. the load-bearing area. There is no evidence of toughness-dependent fracture, in spite of the presence of as-welded (not normalized) material at the bond line. The fracture toughness of the bond line has not been measured in the present work, and from the macrostructure of Fig. 2 would be expected to vary across the pipe wall. The average Charpy energy of the weld at room temperature is 32 J and drops rapidly to lower values with decreasing temperature (Table 3), indicating that the material is at the lower end of the transition range and could be expected to support rapid propagation of a cleavage crack once a crack initiated, perhaps after some ductile tearing. In any case, the static toughness is evidently sufficiently high to resist fracture initiation at stresses up to yield. The largest flaw found (Fig. 6) was approximatly 10 mm diam. The stress intensity factor of this flaw at the observed fracture stress of 550 MPa is $K = (2/\pi)\sigma(\pi a)^{1/2} \approx 44\ \text{MPa}\sqrt{\text{m}}$. which is equivalent to a CTOD of ≈0.016 mm calculated by the relation $\sigma\delta = K^2/E$ with $\sigma \approx 590$ MPa and $E \approx 205$ GPa. At these high stress levels, elastic-plastic fracture mechanics should really be used to estimate toughness at failure. Figure 9 shows that the failure stress of flawed material is at least within 5% of the collapse stress given by the straight line. Then, using a collapse strip yield model

$$\Phi = \frac{4}{\pi^2}\left(\frac{Y\sigma_{pc}}{\bar{\sigma}}\right)^2 \ln\left[\sec\left(\frac{\pi}{2}\,\frac{\sigma}{\sigma_{pc}}\right)\right]$$

where

$$\Phi = \frac{\delta}{2\pi a\,(\bar{\sigma}/E)}$$

$\bar{\sigma}$ = flow stress

Y = geometry factor from $K = Y\sigma(\pi a)^{1/2}$

($Y = 2/\pi$ for circular flaw)

with $\sigma/\sigma_{pc} = 0.95$, we find $\delta = 0.038$ mm. The conclusion is that, even if the toughness is as low as $\delta = 0.04$ mm, flaws of diameter ≤10 mm will not reduce the failure stress more than 5% below the collapse stress based on the product of flow stress and net (excluding flaw) remaining section.

The present work indicates that small flaws up to about 10 mm dia, do not initiate brittle fracture in ERW welds during monotonic loading at low stresses up to yield level, even if the welds are incompletely normalized and susceptible to brittle fracture in the absence of flaws. This does not mean, of course, that the flaws would not degrade the fatigue strength or resistance to sulfide stress corrosion.

CONCLUSIONS

For the ERW pipe tested in the present work, artificial defects up to 10 mm diam at the bond line did not cause brittle (toughness dependent) fracture. The tensile strength can be described by a collapse model in which the strength is proportional to the net load-bearing area.

ACKNOWLEDGEMENTS

The help of Stelco in providing all materials for this phase of work is greatly apprreciated. We would also like acknowledge the techniçal contribution of E.D. Smith and the quantitative metallographical work by B.R. Casault.

REFERENCES

1. Williams, D.N. "A method for evaluating the ductility of the seam weld in ERW pipe"; AGA NG-18 Report No. 141; AGA catalog L51458; 1984.
2. Wang, K.C., Roy, G. and Tyson, W.R. "Plastic collapse stresses of plates with surface grooves"; Division Report ERP/PMRL 83-32(OP-J) and Modelling problems in crack tip mechanics, Proceedings CFC10, Waterloo, Ontario, 1983; Martinus Nijhoff, pp 335-344; 1984.

Table 1. Chemical composition of ERW pipes (ladle, wt%)

C	Mn	P	S	Si	Cb	V	Ti
0.06	1.30	0.010	0.007	0.14	0.041	0.03	0.008

Table 2. Pipe tensile data (mill)

YS (MPa)	UTS (MPa)	El (2 in) (%)	Y/T (%)
522	588	38	89

Table 3. Full size Charpy V notch data

		Energy (J)				Shear (%)			
Position	Temp (°C)	1	2	3	Avg	1	2	3	Avg
Body	-5	129	132	151	137	100	100	100	100
	-20	118	98	124	113	90	87	93	90
	-40	59	112	98	89	62	78	68	69
	-60	15	26	66	36	13	16	22	17
	-75	14	10	28	17	4	3	14	7
Weld	+20	36	27	32	32	43	32	39	38
	-5	16	17	16	16	30	25	20	25
	-20	20	25	8	18	23	13	14	17
	-30	15	7	9	10	19	10	13	14
	-40	5	6	7	6	4	7	6	6

Table 4 Tensile test results of ERW pipes and welds

Specimen ID	Failure mode	% El 50 mm	Tensile MPa	Strength Ksi	Flaw No.	Flaw area mm^2	Flaw % notch section
Pipe body (ASTM E8)							
PA†	d	42.0	544.0	78.9			
PB†	d	40.0	544.0	78.9			
PC†	d	39.0	558.7	81.0			
PD	d	43.6	549.5	79.2			
PE	d	40.0	545.8	79.2			
Average		40.9	548.4	79.4			
Pipe body (notched)							
P1†	d	12.0	617.0	89.5			
P2†	d	15.0	616.7	89.4			
P3†	d	12.0	618.0	89.6			
P4	d	13.5	622.4	90.3			
P5	d	14.9	623.0	90.3			
Average		13.5	619.4	89.8			
Weld (notched) - No flaw							
8	b	3.6	666.0	96.6			
13	b	2.6	601.4	87.2			
15	b	5.7	687.0	99.6			
16	d	10.0	*653.0	*94.7			
20†	d	10.0	*675.2	*97.9			
Average			656.5	95.2			
Weld (notched) - with flaw							
1†	d	5.0	*657.8	*95.4	4	27.3	4.9
2	d	10.0	680.0	98.6	2	49.6	8.8
4	d	8.7	553.0	80.2	3	94.9	16.9
7†	b	2.0	*618.2	*89.7	3	37.3	6.6
9†	d	5.0	*603.9	*87.6	1	71.8	12.8
10	d	7.8	550.0	79.8	6	91.3	16.3
14	b	2.6	631.0	92.0	8	50.7	9.0
21	b	3.5	622.6	90.3	2	61.4	10.9
22†	b	3.0	*679.2	*98.5	6	6.8	1.2
24†	b	6.0	*678.2	*97.9	3	2.7	0.5

† tested with universal hydraulic testing machine under load control; others were tested under displatement control.

d - failed in ductile mode.

b - failed in brittle mode.

* tensile strength calculated based on the average thickness in the weld = 14.73 mm, the others were calculated based on the measured value.

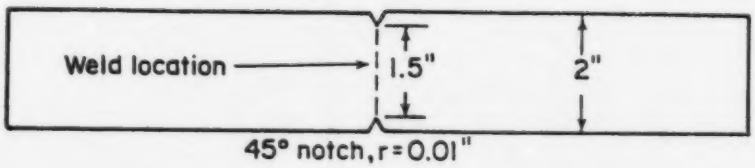

Fig. 1. Tensile specimen used in this work.
(neg 17079)

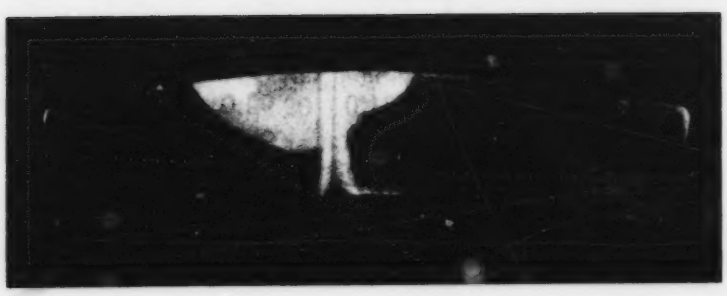

Fig. 2. Lightly etched cross-section of as-received pipe.
(neg 17570)

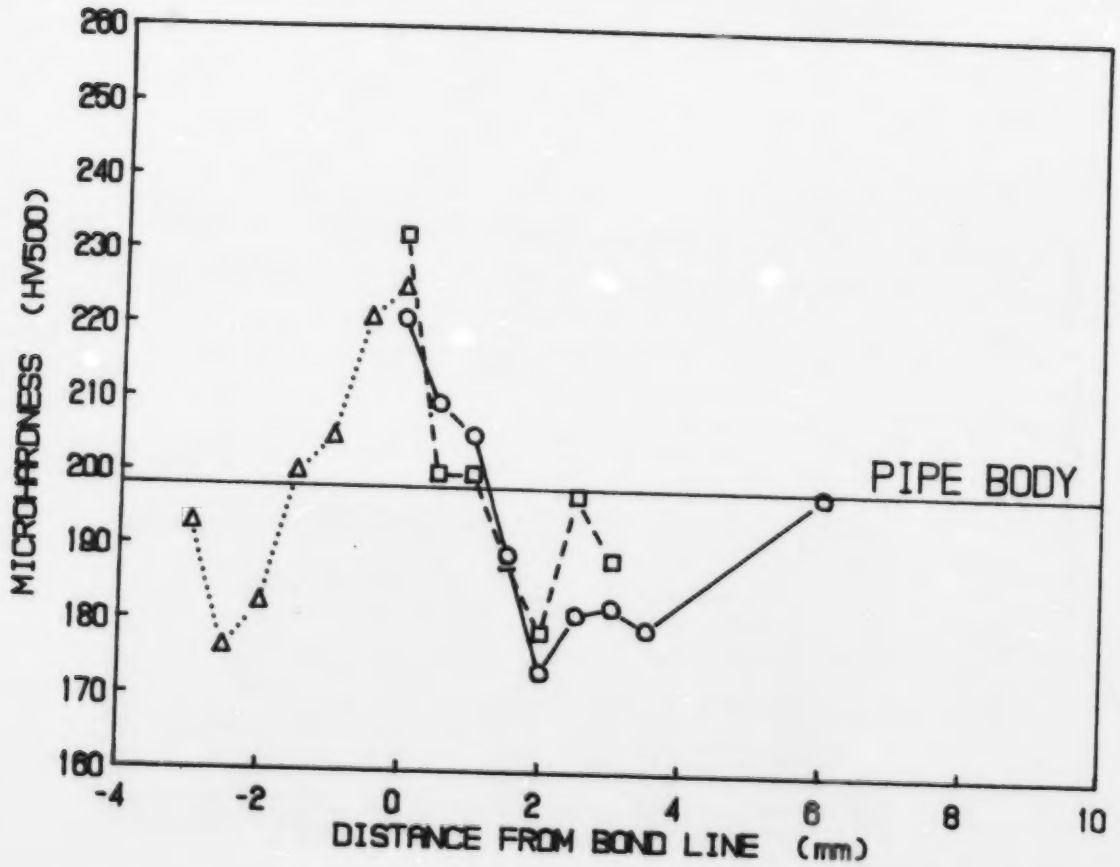

Fig. 3. Hardness traverses across ERW bond line taken from inside surface. Symbols identify three different welds. (neg 17721)

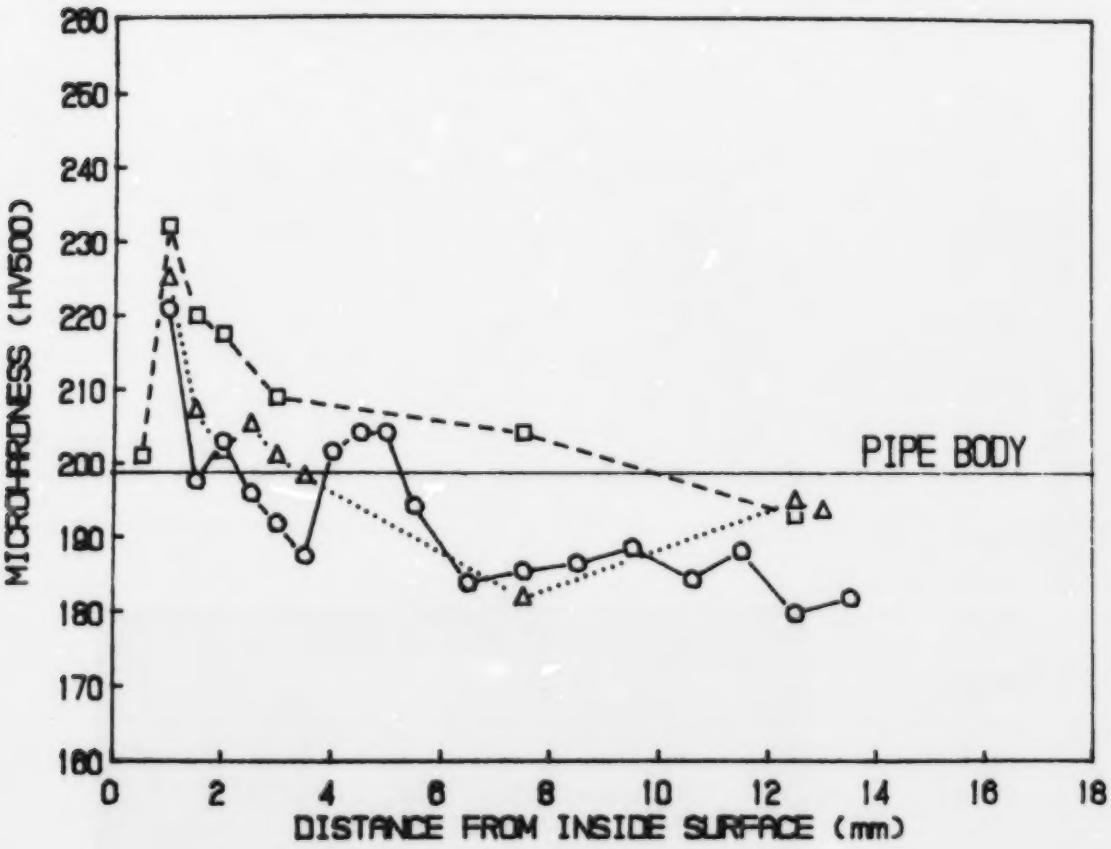

Fig. 4. Hardness traverse along weld line inside to outside surface. Symbols as in Fig. 3. (neg 17722)

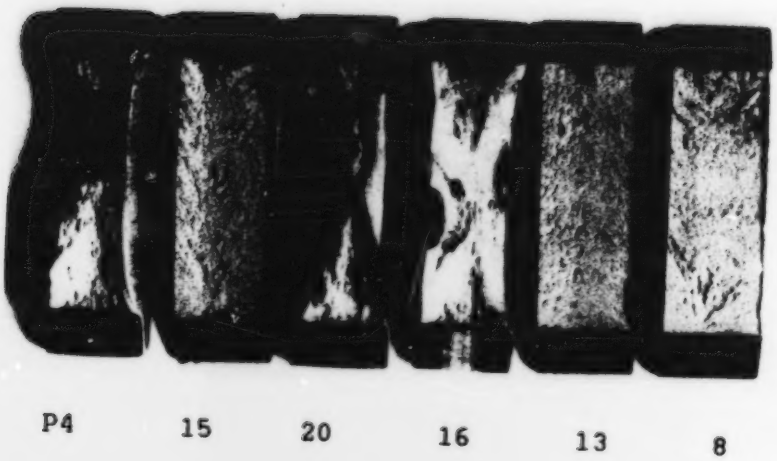

Fig. 5. Fractured notched tensile specimens of ERW pipe welds without flaws. Numbered samples are notched at weld line; P4, notched in pipe body, is included for comparison. (neg 15989)

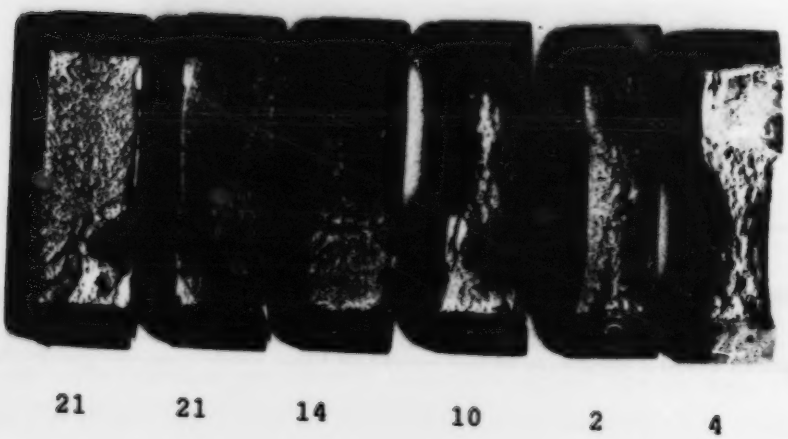

Fig. 6. Fractured notched tensile specimens of ERW pipe welds with flaws. (neg 15988)

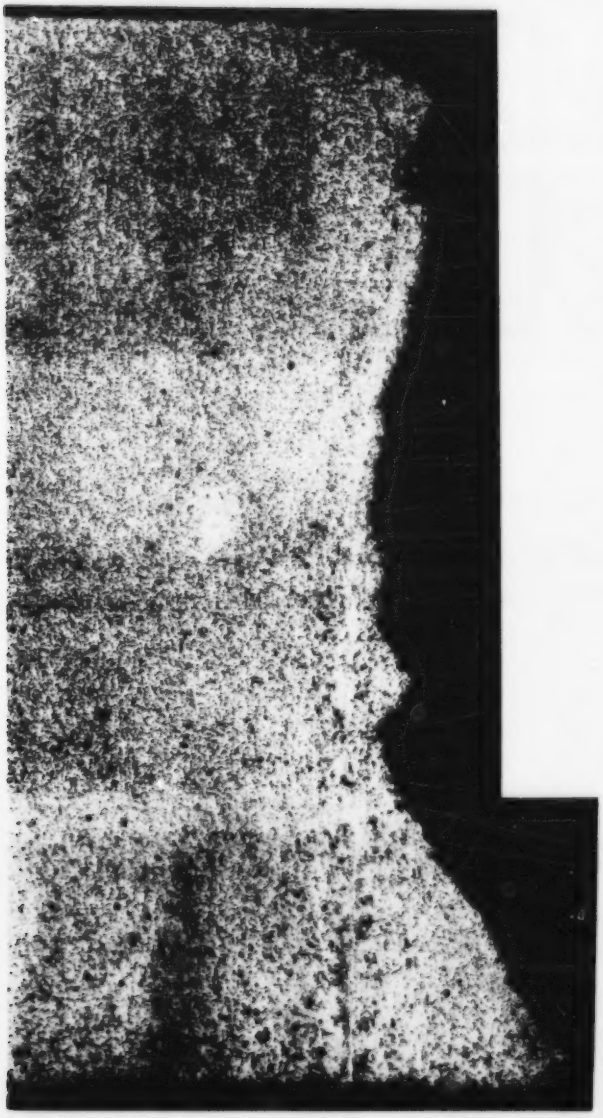

Fig. 7. Macrograph of section through Sample 9 (ductile). The fracture path is near the bond line for about two thirds of the plate thickness, but follows the heat-affected-zone boundary near the inside surface.

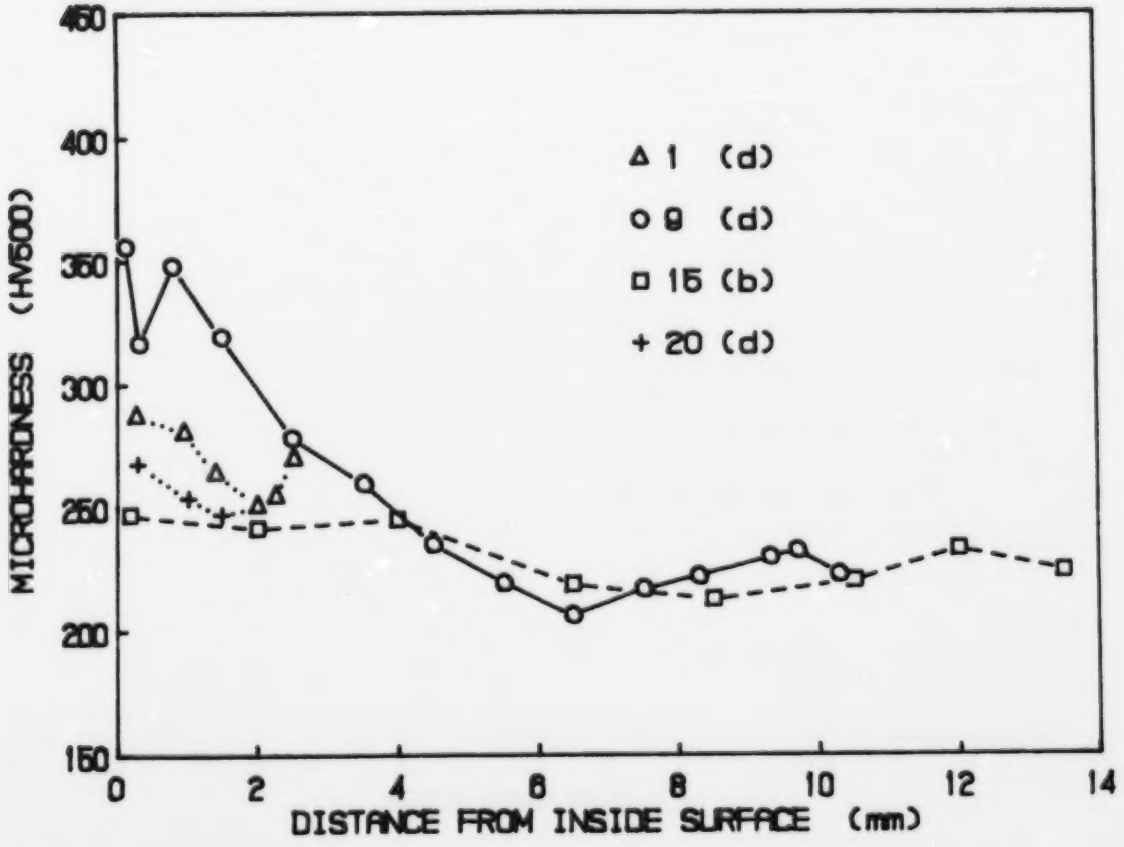

Fig. 8. Hardness traverse along weld line from inside to outside surface of pipe on sections through fracture surfaces of tested samples. (neg 17718)

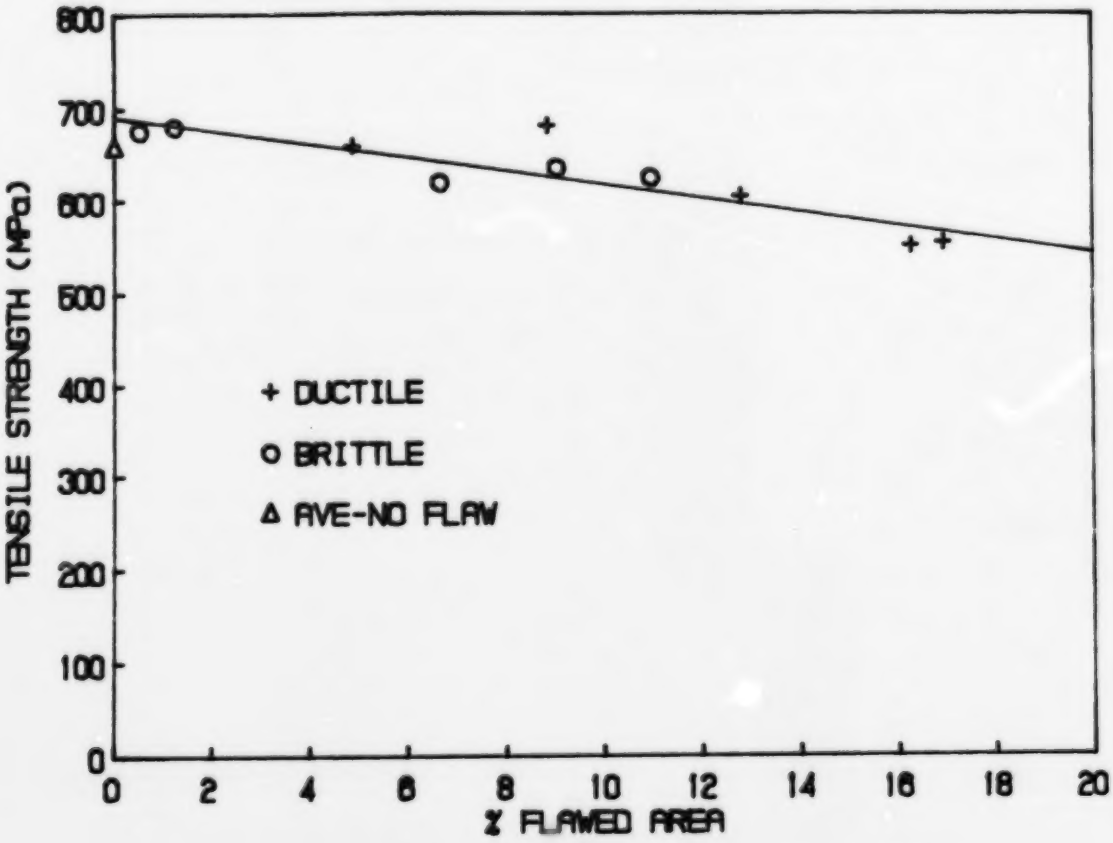

Fig. 9. (Notched) tensile strength of ERW weld samples containing artificial flaws. (neg 17716)